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Review

Interoperability of the Time of Industry 4.0 and the Internet of Things

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Abstract: Industry 4.0 demands a dynamic optimization of production lines. They are formed by sets of heterogeneous devices that cooperate towards a shared goal. The Internet of Things can serve as a technology enabler for implementing such a vision. Nevertheless, the domain is struggling in finding a shared understanding of the concepts for describing a device. This aspect plays a fundamental role in enabling an "intelligent interoperability" among sensor and actuators that will constitute a dynamic Industry 4.0 production line. In this paper, we summarize the efforts of academics and practitioners toward describing devices in order to enable dynamic reconfiguration by machines or humans. We also propose a set of concepts for describing devices, and we analyze how present initiatives are covering these aspects.

Keywords: Internet of Things; Industry 4.0; semantic web; ontology; intelligent interoperability; dynamic production processes

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1. Introduction

The manufacturing industry is currently moving towards more connected and smarter manufacturing chains with optimized supply processes [1]. Smart manufacturing networks integrate heterogeneous data collected across the supply chain for achieving business goals. This trend is, amongst others, captured in the vision of the Industry 4.0 that is focusing on creating intelligent products and production processes [2]. Ultimately, it represents a convergence of information technology and operational technology: supply and production chains will dynamically adjust themselves in order to provide on-demand customization of manufacturing of on-demand customer-driven products.

From a business point of view, Industry 4.0 fosters permanent (or temporal) cooperation among end-to-end, geographically-disperse manufacturing systems. This cooperation is centered on a shared value-chain built by sharing and coordinating (i) people, (ii) manufacturing data, (iii) operational processes, and (iv) sensors and actuators [3]. The production of physical products should also be integrated with supply chain(s) in order to foster optimal distribution [1].

In this context, both production lines and supply chains are trying to take advantage of the sparse collection of sensors and actuators for optimizing their value chain. Consequently, devices are playing a central role in these production lines, which are becoming more and more complex and extremely difficult (if not impossible) to monitor and control by humans. This trend fosters the creation of devices that are capable of dynamically sensing and adjusting themselves in order to optimize the production processes.

The Internet of Things (IoT) and Web of Things research is trying to implement such devices, and consequently, these research domains may serve as a technology enabler for (i) collecting, (ii) storing, (iii) elaborating, and (iv) acting upon the information that is produced and shared among all the value chains. Nevertheless, devices without the capability to adjust themselves to the environment cannot dynamically participate in the production line in Industry 4.0 due to the increasing complexity, which is beyond human reach. Consequently, "intelligent interoperability" plays a critical role in "enabling the enabler" in ensuring the central role that research initiatives in the area of IoT should play in Industry 4.0. In other words, devices should be equipped with the capability of describing themselves in a way that is understandable by both machines and humans; thus, fostering an implicit or explicit semantic description of themselves. Industry 4.0 academics and practitioners commonly accept this need, and a set of case studies and best practices was first introduced by Herman et al. [4].

This paper intends to survey and categorize the efforts of academics and practitioners to enrich the interoperability of devices as described by the IoT domain with a semantic description of the device itself in order to foster dynamic readjustments of themselves with the respect to the system in which they are. This autonomous behavior will play a critical role in designing the production lines fostered by the Industry 4.0 vision due to the increasing complexity, which is beyond human reach.

The research domain of IoT is presenting itself as a scattered collection of activities in several different venues. The terminology used reflects this reality; in particular: sensor network, mobile sink, mobile agent, and mobile data collectors usually mean the same thing. In addition, some researchers borrow terms like actuator or invent specific new terms like "mole" for similar things. This is empathized by the fact that the various sub-communities do not share a single vision, and the term interoperability has a different meaning, which includes: (i) protocol efficiency in terms of data lengths and energy consumption, (ii) methods and functionalities, (iii) interoperability with computational infrastructure, and (iv) the use of meta information for enabling some reasoning.

Nevertheless, the domain does not show relevant controversies; however, researchers of different areas are contributing to it, and consequently, they are not completely aware of the various directions on how the field is evolving. Finally, no significant results have shaped or radically changed the field. The most notable trend is that computational power is becoming less expensive, and this is serving as an enabler for increasing the pervasiveness of the solutions.

The literature that we will present in Section 2 takes into account scientific works that focus on an ontology-based description of devices and other initiatives that prefer an unstructured approach.

A clear outcome of this survey is that several initiatives are trying to model different aspects of a device from different angles. However, Industry 4.0 demands (i) convergence of meaning for the various concepts and (ii) emphasis on the actuator aspects of the devices [1].

Subsequently, in Section 3, we will propose a set of concepts that should be taken into account for modelling a device, and we will look at how these aspects are covered by the most mature initiatives. Finally, Section 4 will summarize and conclude this literature review with our remarks.

2. Related Work

In order to foster the "intelligent interoperability" of the devices, we will consider the efforts that intersect ontology design and the IoT, leveraging both the explicit and implicit semantic description of devices. In the domain of IoT, ontology design focuses on the creation of IoT ontologies and presenting best practices with related methodologies.

In order to achieve an "intelligent interoperability", Papazoglou and Elgammel in [1] envisioned a Manufacturing Reference Architecture (MRA) for Smart Manufacturing Networks (SMNs). This reference architecture deals with wide-ranging interoperability requirements. In particular, the authors leverage Service-Oriented Architecture (SOA) technologies for converting products, processes, and resources into digital services. The MRA service-oriented approach deals mainly with syntactic interoperability issues. However, the use of web services alone does not facilitate a shared understanding of the meaning of data. The Product and Knowledge Management module in their envisioned Manufacturing Blueprint Environment (as described in [5]) contains knowledge templates that intend to deal with semantic interoperability without specific descriptions. This paper will try to generalize this approach and use the term "intelligent interoperability" for referring to any techniques that foster a dynamic and smart reconfiguration of devices for implementing a defined business process.

2.1. A Semantic Approach for Achieving Intelligent Interoperability in Industry 4.0

Semantic web principles and technologies can serve as semantic interoperability providers. In particular, semantic web technologies such as the Resource Description Framework (RDF), the Resource Description Framework Schema (RDFS), the Simple Protocol and RDF Query Language (SPARQL), the Web Ontology Language (OWL) [6], and a few others have been developed to facilitate shared meaning in the distributed web environment. The development of common conceptualizations, known as ontologies, enable shared meaning of data. OWL [7] facilitates the creation of such ontologies as a W3C standard language. RDF and RDFS can be linked to OWL in order to allow a distributed adoption of these ontologies, such as importing from other online available ontologies.

In order to develop sound and effective ontologies, practitioners developed several methodologies; that is, for example, the case of Noy and McGuinness in [8] or Suárez-Figueroa in [9] where they presented a set of best practices that are relevant for Industry 4.0 and IoT, as well. In addition, Gyrard, Serrano, and Atemezing in [10] have discussed the IERC-A4C's best practices and recommendations for semantic interoperability with a specific focus on IoT, where they presented semantic web best practices fine-tuned for this particular case.

One of the cardinal principles in ontology design consists of reusing existing ontologies. This is not always easy to achieve as it requires a systematic collection and categorization of relevant works. For this purpose, the Linked Open Vocabulary (LOV) (http://lov.okfn.org/) is the most well-known catalogue of semantic vocabularies used by academics for sharing their works. It currently lists 22 IoT-related ontologies. However, they are not the only works that are relevant for achieving "intelligent interoperability", as Gyrard, Bonnet, Boudaoud, and Serrano in [11] found over 200 ontology projects related to IoT that have been unlisted in the LOV. The main reasons for this cleaning include: (i) they do not meet the LOV quality requirements; or (ii) they were not leveraging previous works.

So as not to lose all these works, Amelie Gyrard created a catalogue independent of LOV and specialized in ontologies for the Internet of Things (LOV4IOT) (http://sensormeasurement.appspot.com/?p=ontologies) that currently lists 382 (as of on 30 December 2018) ontology-based research works.

This was not the first time that standardization bodies have tried to harmonize the work from practitioners and academics. In fact, W3C in 2009 did the first major attempt at sorting and selecting existing ontologies relevant to the IoT domain. This initiative fostered the creation of the Semantic Sensor Network (SSN) ontology that was created by the SSN workgroup after the review of 17 existing ontologies and data models. In the same year, Compton, Henson, Lefort, Neuhaus, and Sheth in [12] did a peer reviewed survey of sensor ontologies developed. Despite the extensive work, practitioners believe that the SSN is not a complete ontology for the IoT domain. Consequently, academics developed many new ontologies to fill the gaps, as reported in [13], the where authors shared a first step towards a more IoT-focused set of ontologies. This is not the only relevant initiative as Hachem, Teixeira, and Issarny in [14] introduced an ontology-based knowledgebase for the design of IoT middleware solutions. In particular, the knowledgebase focuses on heterogeneous devices and device data.

Bajaj et al. [13] surveyed an extensive amount of ontologies in the IoT domain, at both a generic and domain-specific level of generality, as defined by Ye, Coyle, Dobson, and Nixon in [15]. According to their findings, none of the ontologies are comprehensive and struggle in documenting all the key concepts for semantically annotating end-to-end IoT applications. Due to the extensive list, the authors did not offer in-depth evaluations of all ontologies. Nevertheless, Bajaj et al. concluded that due to the influence of use cases or systems for which the ontologies are developed, the ontologies are system specific and not useful outside their own applications.

All the presented works outline the fact that the developers of projects in the IoT community design their own ontologies without trying to reuse existing works. This approach harms the attempt of defining a shared understanding of what "intelligent interoperability" and clearly outlines the need to reuse existing ontologies.

In particular, if we want to follow the guidelines presented by the authors in [10], we need to focus on defining a clear set of key concepts that will represent a core, shared understanding of the representation of a device. Bajaj et al. [13] initiated this effort and introduced their own key concepts for evaluating existing ontologies; however, their key concepts did not include actuators, which are fundamental for Industry 4.0, and mainly focused on sensing the environment.

Another attempt at defining a set of key concepts was performed by Seydoux, Drira, Hernandez, and Monteil in [6]; in particular, they evaluated LOV-approved generic IoT ontologies on the following key concepts: (i) device; (ii) software agent; (iii) sensor; (iv) observation; (v) actuator; (vi) action; (vii) service; (viii) energy; and (ix) lifecycle. As result, their proposed ontology is considered one of the best for describing IoT devices according to an assessment performed by the authors. In particular, it shows that only five out of the nine evaluated ontologies represented actuators to some degree.

The following table, Table 1, shows an overview of the related work on the semantic web for IoT ontologies and ontology development that we believe are relevant for achieving "intelligent interoperability" in Industry 4.0 case studies.

The research domains of the Internet of Things and semantic web are extremely active and scattered at the same time. Consequently, it is very hard to track progress and initiatives, as also outlined by Andročec et al. [16]. We believe that this subset of works can serve as an "entry point" for researchers that are not familiar with these domains in order to understand core concepts and grasp future research directions without suffering from information overload.

2.2. Relevant Unstructured Knowledge Representation for IoT and Industry 4.0

Several academics and practitioners represent key concepts of the IoT domain using an unstructured knowledge representation, as well. That is, for example, the case presented by Lelli et al. in [12], where the authors described an abstraction model that represents a generic instrument within their Instrument Element solution. The challenge of connecting heterogeneous scientific instruments with the computational infrastructure for remote control and monitoring is similar to syntactic interoperability challenges in IoT devices. The authors conceptualized a device in a more operational and abstract manner, they described the device to consist of a set of parameters, commands, a control model, and an XML-based description of the instrument that can be improved with a semantic description. The Instrument Element solution is a proven solution for dealing with heterogeneous and distributed devices, has been implemented in several use cases, and offers an insight into the basic building blocks of a control system for a complex system of devices.

Other technologies besides formal ontologies also strive to create shared understanding of meaning: the schema.org (https://www.schema.org) initiative, which intends to create a shared vocabulary on the web. Major search engines, Google, Yahoo, Bing, and Yandex, started this initiative, and their defined concepts can be used with microdata, RDFa, or JSON-LD in order to add semantic descriptions of a website in its metadata. Schema.org has expanded beyond the initial intention of the founders; however, the proposed language is not as expressive as OWL and does not intend to support features such as automated reasoning. Nevertheless, it is a well-adopted approach for reusing shared vocabularies that can also be understood by the major search engines. The schema.org initiative has also gathered attention from the IoT community (https://iot.schema.org), but at the moment, the most valid outcome is a discussion of how schema.org could be used in IoT contexts.

Table 1. Works in semantic IoT that are relevant for achieving an "intelligent interoperability" in Industry 4.0. SSN, Semantic Sensor Network.

Citation	Type	Description	Key Findings/Relevance
Bajaj, G., Agarwal, R., Singh, P., Georgantas, N., and Issarny, V. (2017). A study of existing Ontologies in the IoT-domain.	Survey	Provides an overview of the existing semantic ontologies to date and reviews their shortcomings based on self-defined fundamental ontological concepts for IoT-based applications.	Clarifies the state-of-the-art of semantic solutions for IoT. It provides a set of fundamental semantic concepts for IoT. It also clearly articulates why there is a need for a common unified ontology for the IoT domain.
Compton, M., Henson, C., Lefort, L., Neuhaus, H., and Sheth, A. (2009). A survey of the semantic specification of sensors. Proceedings of the 2nd International Conference on Semantic Sensor Networks, 522, pp. 17–32.	Survey	Reviews twelve sensor ontologies that were relevant prior to the creation of the SSN in 2009.	Existing ontologies cannot express the required properties of the desired capabilities.
Ghanza, M., Paprzycki, M., Pawlowski, W., Szmeja, P., and Wasielewska, K. (2017, March 1). Semantic interoperability in the Internet of Things: An overview from the INTER-IoT perspective. Journal of Network and Computer Applications, 81, 111-124.	Survey	Find how ontologies and semantic data processing can facilitate interoperability. Investigate available ontologies for IoT in general and for two specific use cases, (e-/m-)health and port transportation and logistics.	Provides a list of general IoT ontologies with a short description for each, although many of the listed IoT ontologies are strictly sensor based. The lists of ontologies for both (e-/m-)health and for port transportation and logistics are vast.
D. Andročec, M. Novak and D. Oreški, (2018) Using Semantic Web for Internet of Things Interoperability: A Systematic Review. International Journal on Semantic Web and Information Systems (IJSWIS) 14-4	Survey	Review of 105 articles that try to address the interoperability issue in the domain of IoT, listing the type of ontologies used by academics until 2016	The systematic review outlines a very dynamic field and focuses strictly on the IoT domain. Given the maturity of semantic web, consolidation is encouraged
Gyrard, A., Serrano, M., and Atemezing, G. A. (2015). Semantic Web Methodologies, Best Practices and Ontology Engineering Applied to Internet of Things. IEEE World Forum-Internet of Things (WF-IOT)	Best Practices	Presents a set of best practices designed by the semantic web community. Suggests that the IoT community should follow this approach, and provides 3 use cases where to apply them.	16 best practices for ontology design relevant for the IoT domain. Recommendation of a set of tools. A checklist for evaluating the compliance with the best practices.
Noy, N. F., and McGuinness, D. L. (2001). Ontology development 101: A guide to creating your first ontology.	Ontology design methodology	Illustrates what an ontology should look like. It then provides a simple stepwise approach to ontology design; while also addressing complex issues that arise while creating ontologies.	The ontology development methodology consisting of 7 steps is the main contribution. This work is also a valid tutorial for ontology creation.
Suárez-Figueroa, M. C. (2010). NeOn Methodology for building ontology networks: specification, scheduling and reuse	Ontology design methodology	Doctoral thesis that focuses on advancing the ontology engineering field and suggests the creation of a methodology for building ontology networks.	A methodology that defines activities in ontology creation very precisely.
Hachem, S., Teixeira, T., and Issarny, V. (2011). Ontologies for the Internet of Things. *ACM/IFIP/USENIX 12th International Middleware Conference*.	IoT Ontology	Presents challenges for the IoT related to scalability, heterogeneity, and unknown network topology. Suggests a service-oriented middleware solution that facilitates interoperability.	Presents how to use a knowledge base to solve interoperability issues. Suggests a three-layered global IoT ontology that specifies concepts that should be included in the ontology.

Table 1. *Cont.*

Citation	Type	Description	Key Findings/Relevance
Seydoux, N., Drira, K., Hernandez, N., and Monteil, T. (2016). IoT-O, a Core-Domain IoT Ontology to Represent Connected Devices Networks. In E. Blomqvist, F. Poggi, and F. Vitali (Ed.), *EKAW 2016: Knowledge Engineering and Knowledge Management* (pp. 561–576)	IoT Ontology	Introduces the IoT-O ontology; which is a core domain modularized ontology for IoT.	Evaluate ontologies listed in LOV devising a set of required concepts. The proposed IoT-O ontology presents a sound and valid principle of reuse.
Compton, M., Barnaghi, P., Bermudez, L., Garcia-Castro, R., Corcho, O., Cox, S., . . . Taylor, K. (2012). The SSN ontology of the W3C semantic sensor network incubator group. Web Semantics: Science, Services and Agents on the World Wide Web, 17, 25-32.	IoT Ontology	Introduces the SSN ontology and its use in research projects.	The SSN is the only W3C standard for ontologies in the IoT domain. It is one of the major contributions to the field. It provides the basis for many IoT ontology projects.
Agarwal, R., Fernadez, D. G., Elsaleh, T., Gyrard, A., Lanza, J., Sanchez, L., . . . Issarny, V. (2016). Unified IoT ontology to enable interoperability and federation of testbeds. 2016 IEEE 3rd World Forum on Internet of Things (WF-IoT), (pp. 70–75). Reston, VA.	IoT Ontology	This paper introduces the FIESTA-IoT ontology and the M3-lite ontology; together with tools for adapting the presented common ontology in datasets.	The FIESTA-IoT ontology contributes by bundling the combined efforts of stable popular ontologies. The byproduct, M3-lite, is a sound specification of domain knowledge.
Bermudez-Edo, M., Elsaleh, T., Barnaghi, P., and Taylor, K. (2016). IoT-Lite: A Lightweight Semantic Model for the Internet of Things. 2016 Intl IEEE Conferences on Ubiquitous Intelligence and Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People, and Smart World Congress (UIC/ATC/ScalCom/CBDCom/IoP/SmartWorld), (pp. 90–97). Toulouse.	IoT Ontology	Provides evidence for the lack of widely-adopted IoT ontologies and the lack of lightweight solutions. Introduces ten rules for good and scalable semantic model design. Following those rules, the IoT-lite ontology is created and introduced.	The major contribution is the creation of a lightweight ontology for IoT by extending the SSN ontology. The IoT-lite ontology was proven more suitable for dynamic and responsive environments than a direct competitor was.

One of the main benefit of this approach is that is possible to create a shared understanding of the meaning of data without introducing the additional complexity of the creation of an ontology. In addition, a mapping between schema.org and an ontology is possible as it represents things and the connections they have. This is supported by several research works; in particular, Davis, Shrobe, and Szolovits [16] remark that ontologies can be made in various languages and notations, but that the content is what is essential, especially the components and connections. In addition, Wache et al. [17] found that besides description logic or frame-based languages for representing ontologies, other approaches exist; however, these would not be considered as real ontologies from a knowledge engineering point of view.

In general, a semi-formal approach, as opposed to formal ontologies, has been shown to be able to handle semantic integration challenges in the semantic web domain. However, most existing IoT ontologies are made with a formal language, more specifically OWL [18]. This is supported by Kalibatiene and Vasilecas [19] where they claim that OWL is the most popular of the ontology languages they surveyed.

In general, all types of languages have advantages and disadvantages, and in the case of OWL, Kalibatiene and Vasilecas [19] found that the complexity and inefficiency of reasoning are the main inhibitors.

Independently of solving the problem of "intelligent interoperability", a formalization of an agreement on how to express relevant aspects of reality is a shared problem, and the principle of reuse provides a good basis for advancing interoperability.

It is commonly, accepted and understood that "The ontologies that will furnish the semantics for the semantic web, must be developed, managed, and endorsed by practice communities" as Shadbolt, Berners-Lee, and Hall in [7] noted. However, practice communities are rarely involved in the IoT ontologies created by academics to date; probably, oneM2M (http://www.onem2m.org/) represents one of the few exceptions, as is a standardization initiative that is currently collaborating with nearly 200 organizations. However, the most crucial challenge faced by the IoT community to serve as a technology enabler for Industry 4.0 is represented by the lack of reuse of domain knowledge [10]. Initiatives like FIESTA-IOT EU (http://fiesta-iot.eu/index.php/iot-experiments-as-a-service/) are trying to fill the current gap, as members are trying to develop a conceptual model for IoT devices within the context of their use cases, which will probably lead to a system-specific ontology.

2.3. Technology for Enabling Intelligent Interoperability among Devices

In this section, we intend to report the technologies that are commonly used by academics and practitioners for implementing their prototypes and proofs of concept. In particular, the authors that are focusing on representing their knowledge in a structured way are concentrating their development effort on "the semantic web stack". At the same time, authors that prefer an unstructured representation focus on schema.org or plain descriptions.

This literature review shows that there is currently no widely-accepted generic IoT ontology that can be used for achieving an "intelligent interoperability" among devices as envisioned by Industry 4.0. Nevertheless, the majority of authors prefer to use "the semantic stack" when developing a case study. The majority of the disagreement is centered on the development of the ontology, and this is reflected by the need to generalize key concepts for a common IoT knowledge infrastructure, upon which domain specific ontologies can be extended without the need to add major generic IoT concepts.

The adoption of structured or unstructured representation of this knowledge is not as important as finding a shared common ground for establishing a set of key concepts for describing devices.

Practitioner and academics are currently using different technologies for expressing meaning from data. On the one side, the semantic web community is using W3C proposed standards, and on the other side, practitioners prefer to adopt lightweight solutions like schema.org. Table 2 below reports a list of tools and technologies that have been reported in this paper and are relevant for defining an intelligent interoperability among Industry 4.0 supply chains.

Table 2. List of acronyms and relevant technologies for structured and unstructured knowledge representation.

Acronym	Meaning	Reference
RMA	Referenced Manufacturing Architecture	Introduced by the authors in [1]
SMNs	Smart Manufacturing Networks	Introduced by the authors in [1]
RDF	Resource Description Framework	Maintained by W3C [1]
RDFS	Resource Description Framework Schema	Maintained by W3C [2]
SPARQL	Simple Protocol and RDF Query Language	Maintained by W3C [3]
OWL	Web Ontology Language	Maintained by W3C [4]
IERC	European Research Cluster on Internet of Things	Research council [5]
LOV	Linked Open Vocabulary	Index of ontologies [6]
Schema.org	Schema.org	Shared vocabulary for the Internet

[1] https://www.w3.org/RDF/; [2] https://www.w3.org/TR/rdf-schema/; [3] https://www.w3.org/TR/rdf-sparql-query/; [4] https://www.w3.org/OWL/; [5] http://www.internet-of-things-research.eu/; [6] https://lov.linkeddata.es/dataset/lov/.

2.4. Current Trends and Late Developments for Achieving "Intelligent Interoperability"

The field of the semantic web is moving towards the "Semantic Web of Things" and rapidly evolving with the creation of new dedicated journals, as well. Consequently, we intend to limit our self to describing the current trends without a structured categorization. This problem is also outlined by Andročec et al. [20]; the article is the most recent survey at the time of writing. The authors were forced to limit the survey to scientific contributions published until 2016, clearly outlining the difficulty of catching a moving target. One of the latest discussions on the Web of Things was presented by Datta et al. [21]. This work outlines a relevant subset of the developments in the research fields of the Internet of Things and semantic web. Several references mentioned in their work could be adopted for achieving "intelligent interoperability" for Industry 4.0.

Please note that these works are particularly new at the time of writing, and in this paper, we intended to survey efforts that are considered relatively mature by the research field. We chose this approach because we believe that IoT and should serve as an enabler for implementing the vision of Industry 4.0 and consequently should be based on relatively consolidated research. Nevertheless, the following set of works are showing promising results. That is the case of Ghanza et al. [22] or Lanza et al. [23], who suggested to foster interoperability among IoT platforms. Traditional works focus on the interoperability at the level of the device for establishing "meaningful conversations". Datta et al. [24] defined a set of criteria for assessing semantic interoperability across IoT, introducing a way to quantify interoperability. Finally, Petel et al. [25] presented the IoT domain as a use case for artificial intelligence techniques in Industry 4.0.

3. Towards Defining a Set of Key Concepts for Describing Industry 4.0 Devices

Defining a set of key concepts for describing devices that will participate in dynamic production lines represents a core feature for Industry 4.0 and a challenge for IoT academics and practitioners. In this section, we intend to describe a set of items that serve as an initial step for finalizing an ontology or an unstructured description that clarifies what a device is from the Industry 4.0 point of view.

One of the goals is to model the fact that multiple sets of devices can be merged to create a set of production processes. Consequently, the key concepts should be able to define a producer (i.e., a production line) and, among others, its production processes. Consequently, our representation should be able to represent (i) sensors, (ii) actuators, (iii) their relationships with the environment, and (iv) how production processes are using them.

We can refer to this set of use cases as concrete examples of what we would like to formalize:

- Predictive maintenance refers to a set of use cases that are relevant to Industry 4.0 and are often mentioned as one of the more common use cases for IoT devices. Predictive maintenance envisions the use of sensors to measure the status of machines and tools that will be used to notify appropriate personnel when preventative maintenances should be performed for preventing future downtimes.

- A more general case would be the use of automated optimization of machine performance based on sensor data and actuator responses to tweak physical settings.
- We should also be able to use actuators for changing the configuration of the machines remotely and/or automatically, following the guidelines of a general production planning.

We can generalize these use cases as a set of connected sensors and actuators. These devices should automatically compose themselves, leveraging the description of their capability in order to support and optimize the production line.

3.1. Concepts for Describing Devices in Industry 4.0

In the context of Industry 4.0, the features of a device can be conceptually divided into five different categories, as reported by the following subsections. These categories should be able to give a different view of the device itself and altogether should provide a uniform description of the devices in a production line.

3.1.1. Functional

This category should cover the functionality of a device. Concepts are focused on the functionality that the device provides and should answer to the following questions:

- What attribute does the device's sensor measure?
- What actions does the device's actuator take?
- What is the functionality of the device?

3.1.2. Contextual

This set of attributes should describe the environment in which the device operates, giving an answer to the following questions.

- Where is the device's geographical and relative location?
- What object is it attached to?
- What process is it involved in?
- At what time were the functions performed?

3.1.3. Procedural

This is a set of concepts related to procedures for explaining which rules govern the devices behavior. Examples includes:

- At which time intervals does the device normally function?
- Under which conditions does the device function?
- What rules does the device follow?

3.1.4. Operational

This involves the information on how the device can be operated by human operators or other devices or systems. Relevant information should answer the following questions:

- To which service is the device exposed?
- What role does the device have, and what privileges does it give?
- How can the device be configured?
- How can the device be controlled?

3.1.5. Descriptive

This refers to the internal information of the device itself and its role in the system that we need to operate. Examples of relevant information should be able to answer the following questions:

- What system is the device a part of?
- What is the devices' hierarchy with regards to devices and systems?
- Which sensors does the device have?
- Which actuators does the device have?
- How much energy does it consume?
- What are the available resources?
- What is the device's health?

3.2. Concepts and Their Relative Importance for Industry 4.0 Devices

Within the five foreseen categories, we can also envision different degrees of importance. In particular, we would like to consider the following three levels:

1. Core: This refers to the attributes that are needed for ensuring a basic functionality of the device in the context of Industry 4.0
2. Desired: This refers to information that will enhance the functionalities of the device and its flexibility; nevertheless, they are not needed to ensure a basic functionality
3. Optional: This refers to information that has similar characteristics to the desired. However, this is of secondary importance

3.3. Comparison of Different IoT Ontologies for Industry 4.0 Devices

Table 3 below contains the most mature IoT ontologies according to LOV plus the IoT as envisioned by schema.org. For each technology, we tried to evaluate their maturity with the respect of the concepts mentioned in Section 3.1. In some cases, the implementation of the concepts is sound, while on other occasions, the concept lacks a desired level of detail; these cases are marked with an asterisk. In addition, schema.org has not yet produced a knowledge representation of the concepts, and its evaluation is based only on the preliminary discussion document.

Table 3. Review of existing ontologies and schema.org.

Technology	**Core**											**Desired**					**Optional**						
	System	Device	Location	Sensor	Actuator	Object	Attribute	Service	Control	Actuation	Measurement	Functionality	Process Association	Time	Conditions	State	Energy Consumption	Resource Consumption	Device Health	Role	Configuration	Procedure	Rule
Fiesta-IoT	√	√	*	√	*	√	√	√			√			√	*								
IoT-lite	√	√	√	√	*	√	√	√			√												
IoT-O	*	√		√	√	√	√	√	*	√	√			√	*		√						
SEASD	√	√		√	√	√	√			*	*		√										
SSN	√	√		√		√	√				√			*	*								
oneM2M*		√		*	*	*	*	√	√	√	√			√									
Schema		√	√	√	√	√	√		√	√	√			√			√						

The W3C Semantic Sensor Network (SSN) is one of the earliest and most reused ontologies focused exclusively on sensing and sensor data. It is meant to be supplemented with additional ontologies to fill gaps in functionality. The IoT-lite ontology was intended to be a lightweight version of the SSN ontology. The ontology was supplemented with additional functionality such as concepts for location and services. One of the premises of this ontology is to design it for optimal performance.

The IoT-lite ontology is meant to be used and extended upon where needed while maintaining a lightweight set of core concepts. It proved to have increased performance over competing ontologies. The IoT-lite ontology is also submitted for standardization as a W3C standard.

The Fiesta-IoT ontology composes concepts from the SSN, IoT-lite, M3 Taxonomy, Time, and DUL ontologies into the Fiesta-IoT ontology. It promises guaranteed semantic interoperability in the IoT domain. Fiesta-IoT also borrows some logic from the more complex IoT-A ontology. The M3-lite ontology is designed to facilitate the Fiesta-IoT ontology with a lightweight version of the M3 taxonomy tailored to the Fiesta-IoT project's needs. M3 taxonomy is a collection of types of sensors that are linked to the SSN sensor concept; the types of sensors range from sensors in the meteorological domain to sensors in the medical domain. Furthermore, the ontology follows best practices and uses concepts from ontologies that use best practices themselves. The ontology is used in testbeds that are part of the Fiesta-IoT project.

The focus of the SSN, IoT-lite, and Fiesta-IoT ontologies is all on sensing and making sensor data semantically interoperable, with the Fiesta-IoT being the most competent in that respect. None of these ontologies goes beyond simply mentioning actuators.

SEASD is a module of the larger SEAS ontology. The SEASD is a device ontology with limited concepts that allows for both sensing and actuating an object and its properties. SEASD does not reuse other existing ontologies.

The IoT-O ontology is based on both the SSN and its actuating counterpart named the Semantic Actuator Network (SAN). The authors of the IoT-O ontology created the SAN themselves. The IoT-O ontology is a modularized ontology that has modules for sensing, actuating, services, lifecycle, and energy. All modules reuse existing work. Furthermore, it integrates with OneM2M standards. The IoT-O ontology was tested on a home automation use case, but offers no further details of it being currently in use in any systems. What is particularly interesting about the IoT-O ontology is the additional conception of the SAN as a basis for actuating, such as SSN for sensing, and the IoT-O's modularized design.

OneM2M is not an LOV-listed ontology; however, it is supported by the OneM2M standards organization for machine-to-machine and IoT. This ontology handles actuating and device control in a more detailed manner if we compare it with SSN, which is centered on sensors. Unfortunately, the OneM2M ontology does not follow best practices and cannot be reused, since it is not freely available. Nonetheless, the logic on actuating is an important feature for Industry 4.0, and some of the concepts should serve as a base for evolving more mature ontologies in this direction.

Schema.org is, in principle, a quite promising and complete approach that could overcome the intrinsic complexity of ontologies; however, it is not yet fully developed.

4. Conclusions

In this paper, we analyzed the interoperability aspects of IoT and argued that a proper implementation can serve as an enabler for advancing use cases envisioned by Industry 4.0. In particular, we suggested that an "intelligent interoperability" may be the key for enabling the dynamic configuration of production lines. Subsequently, we analyzed how academics and practitioners active in the IoT domain are currently addressing the issue of enriching the interoperability of devices with semantic annotations. We found several initiatives in this direction, but the landscape is fragmented and does not present a shared understanding of the concepts that are needed for describing a device for the domain of Industry 4.0.

After the literature review, we suggested a set of concepts that should be part of structured or unstructured knowledge representations of a device. In addition, we analyzed if and how existing initiatives are currently implementing them.

Recommendations for advancing the state-of-the-art of the (intelligent) interoperability of IoT towards solving use cases from Industry 4.0 include:

- IoT can serve as enabler technology for Industry 4.0 especially if proper "intelligent interoperability" is achieved.
- Consider a deeper collaboration among practitioners and academics for developing a shared set of concepts.
- Consider structured knowledge around devices that does not only focus on sensors and includes actuators, as well.
- Schema.org may be a promising technology that could overcome the intrinsic complexity of the semantic web; however, in the case of IoT, it is still in its initial phases.

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